SpaceWorks Engineering, Inc. (SEI)

Automated Hypersonic Launch Vehicle Design Using ModelCenter®

Paper Number: GT-SSEC.B.1
Session Title: Systems Analysis and Systems Engineering
Georgia Tech Space Systems Engineering Conference (GT-SSEC)
November 8-10th, 2005
Atlanta, Georgia

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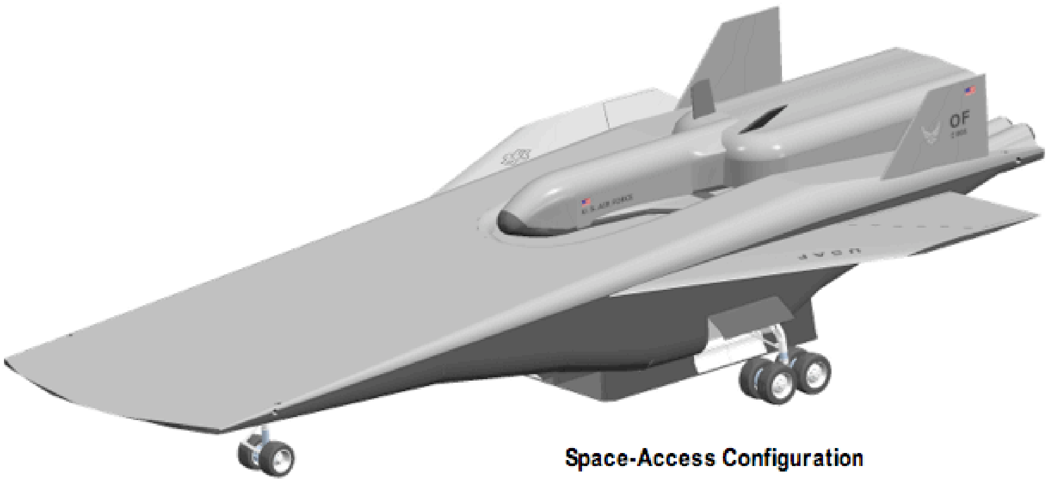
Outline

- Hypersonic Airbreathing RLV Concepts
- Disciplinary Analysis Tools
- High-Fidelity Closure Models
- ROSETTA Meta-Model
- Summary and Conclusions

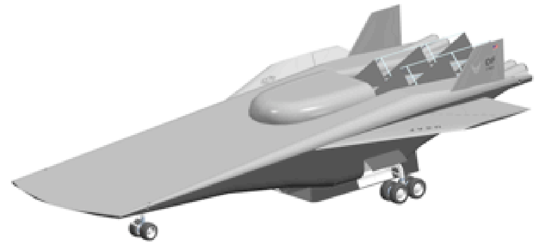
Hypersonic Airbreathing RLV Concepts: *Quicksat* and *Sentinel*

Quicksat TSTO MSP

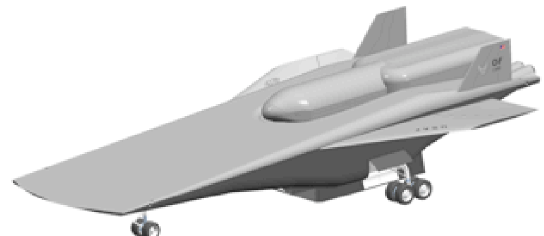
Quicksat MSP



Space-Access Configuration

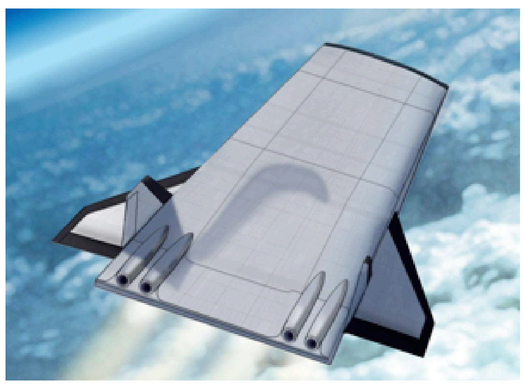


Strike Mission Configuration

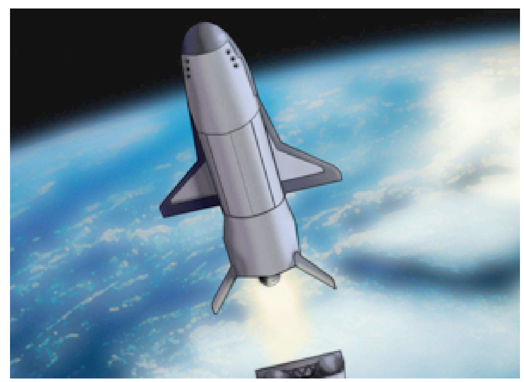


Cargo Delivery Configuration

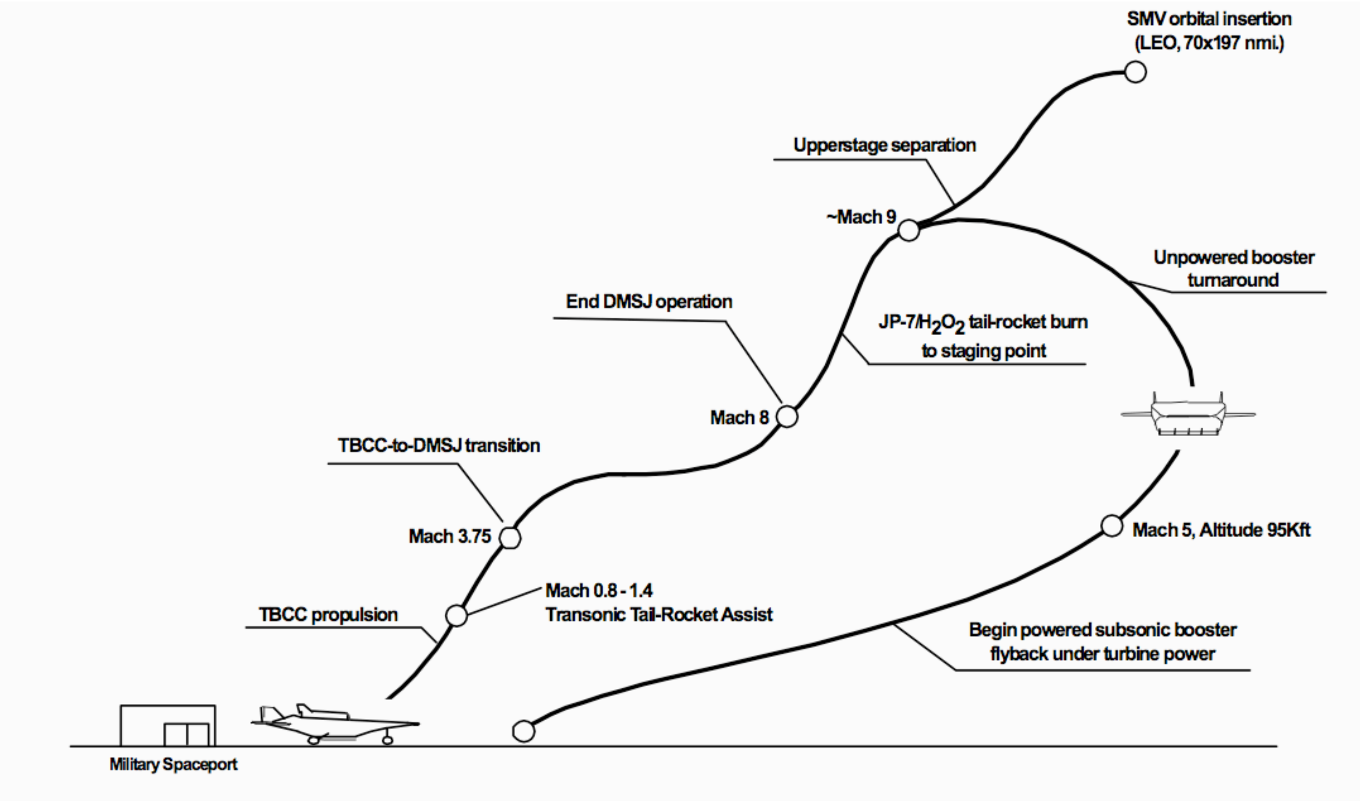
Takeoff from Military Space Port



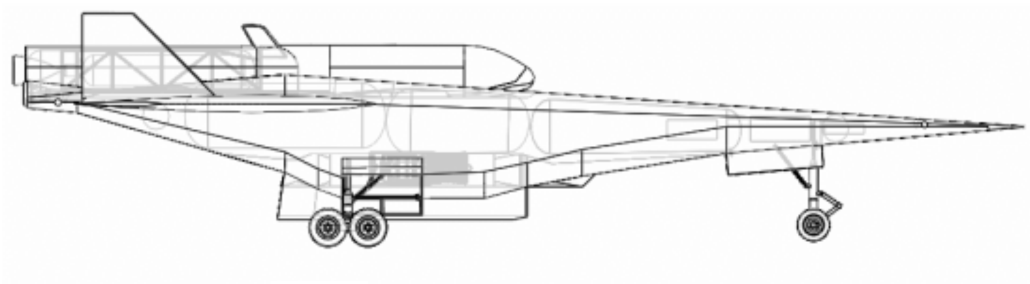
Mach 9 Staging Point

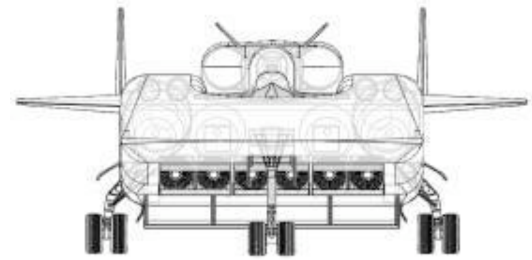


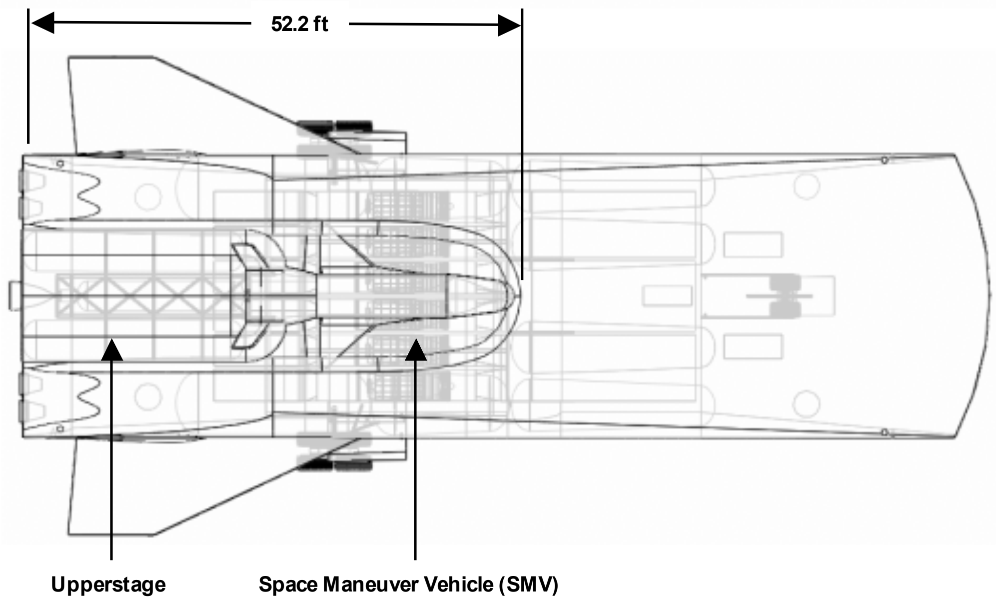
SMV Orbit Delivery to 70x197 nmi. @ 28.5°



Mission Profile: Baseline







Gross Weight – system (lbs):	741,670
Dry Weight – *Quicksat* (lbs):	167,840
Dry Weight – Upperstage (lbs):	4,275
Mass Ratio – *Quicksat*:	2.418
Mixture Ratio – *Quicksat*:	0.390
Length (ft)	123.6
Booster Payload – Upperstage + SMV (lbs):	89,515
Space Maneuver Vehicle – SMV (lbs):	13,090

Integrated *Quicksat/Upperstage* 3-View

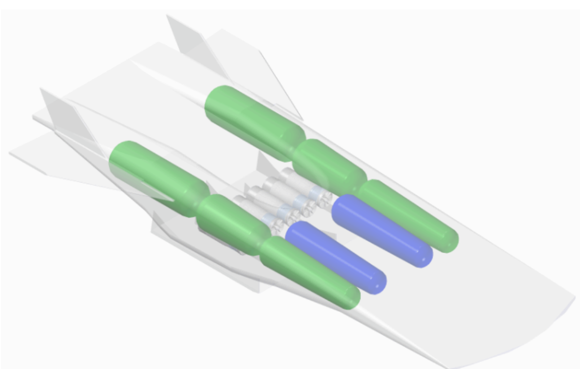
Quicksat Weight Breakdown Summary

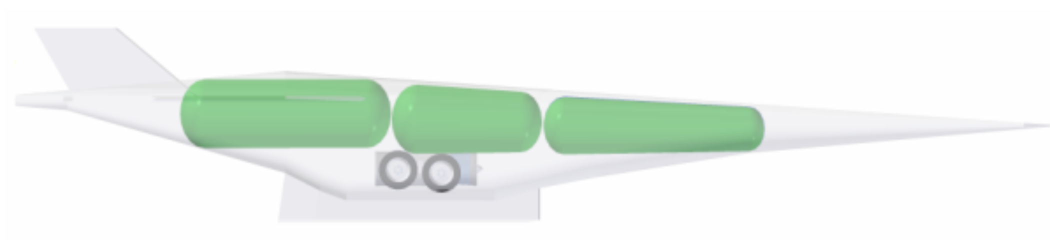
Vehicle Hardware

Component	Weight (lbs)
Wings and Tails (with carry through structure)	14,120
Airframe Structure(bulkheads, tanks, etc.)	39,105
Thermal Protection	14,070
Landing Gear	14,620
Main Propulsion	
TBCC	39,450
DMSJ	13,640
Tail-Rockets	5,585
ACS Propulsion	730
Subsystems (power, EHAs, EC&D, avionics, ECCLS)	8,045
Dry Weight Margin (15%)	18,475
DRY WEIGHT	167,840

System

Component	Weight (lbs)
Booster Dry Weight	167,840
Payload (Upperstage with SMV)	90,215
Residual Propellants	1,035
Reserve Propellants	3,750
LANDED WEIGHT	262,840
Flyback Propellants	25,780
ENTRY WEIGHT	288,620
ACS Propellants	4,855
Unusable Propellants	13,280
INSERTION WEIGHT	306,755
Ascent Propellants	
JP-7 Fuel	312,875
H2O2 Oxidizer	122,040
GROSS WEIGHT	**741,670**
Startup Losses	**4,430**





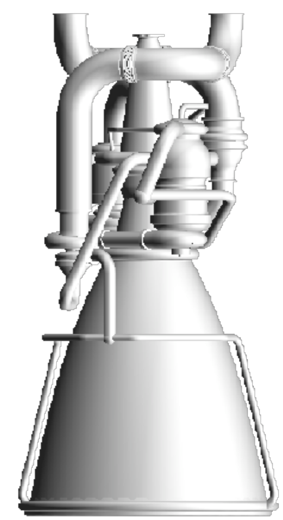
NOTE: Component categories represent rolled up totals from Level-3 Weight Breakdown Statement (WBS)

Liquid Rocket Propulsion Systems

- JP-7 and H2O2 at 95% purity (5% H2O)
- “Staged Combustion”, closed-cycle design with H2O2-catalyst pack for turbine drive gases
- Multiple restart capability (minimum 2)
- Gimbals
- Similar flowpaths on both vehicle stages (different thrust classes):
  - 4 engines aft section of Quicksat
  - 1 engine on Uppersage
- Upperstage engine sized to provide T/W of 1.15 at staging condition (Mach 9)
- Quicksat engines sized to provide T/W of 0.475 at takeoff condition (though not operating, provides abort option)

ENGINE SPECIFICATIONS:

Parameter	Quicksat	Upperstage
Oxidizer/Fuel (OF) Ratio	7.0	
Chamber Pressure – Pc (psia)	2,200	
Area Ratio	50:1	100:1
Isp – Vacuum/Sea-Level (s)	329.91 / 270.24	336.1 / 216.5
Thrust - Vacuum/Sea-Level (lbs)	107,520 / 88,073	102,940 / 66,310
Uninstalled Weight (each, lbs)	1,188	1,393
Engine T/W –Vacuum / SLS	90.5 / 74.1	73.9 / 47.6

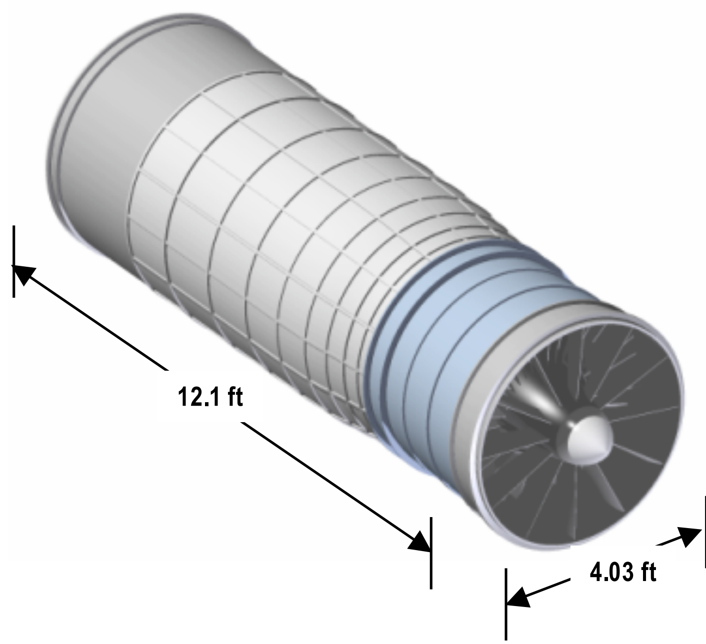


Quicksat Low-Speed Propulsion System

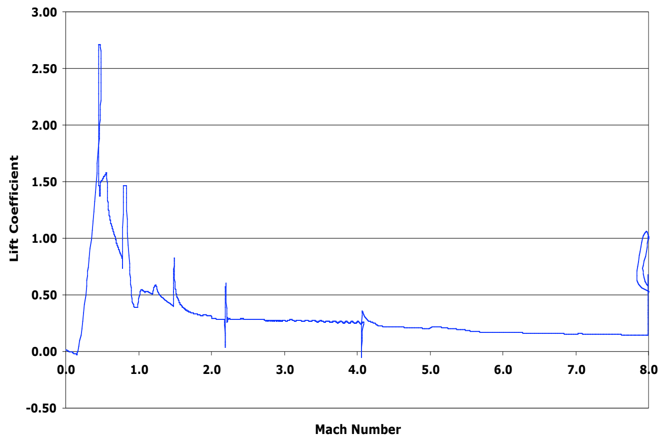
- 6 JP-7 fueled low-bypass ratio turbofans with afterburners
- Forebody/inlet system analysis performed using in-house tools integrated in ModelCenter©
- Engine performance predictions using NASA GRC NEPP code

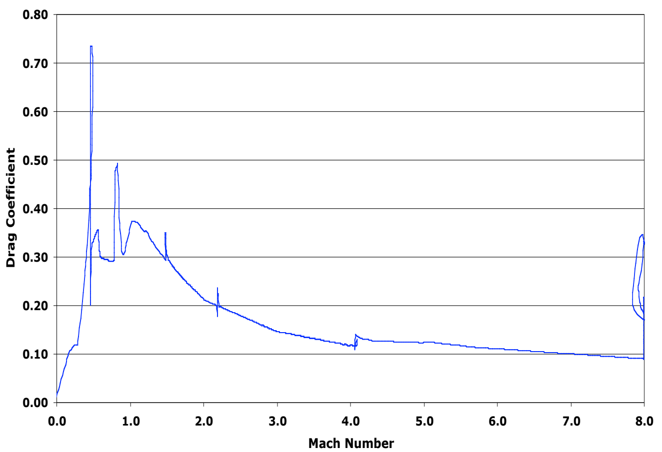
ACTUAL ENGINE SPECIFICATIONS (Scaled Engine):

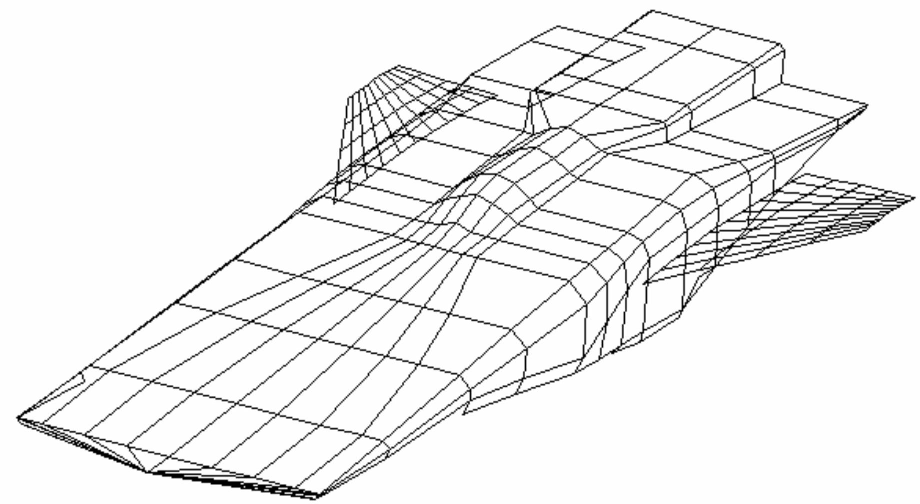
Parameter	Value
Max. Compressor Face Mach Number	0.7
Compressor Face Diameter	4.19 ft
Bypass Ratio	1:1
Overall Pressure Ratio (OPR)	17.5
Core Pressure Ratio (CPR)	5.0
Maximum Effective Turbine Inlet Temperature (TIT)	3,400 R
Uninstalled T/W	15.0
Installed T/W	9.96
Hub-to-Tip Diameter Ratio	0.20
Thrust, SLS (ϕ = 0.95)	65,660 lbs
Isp, SLS (ϕ = 0.95)	1,897 sec

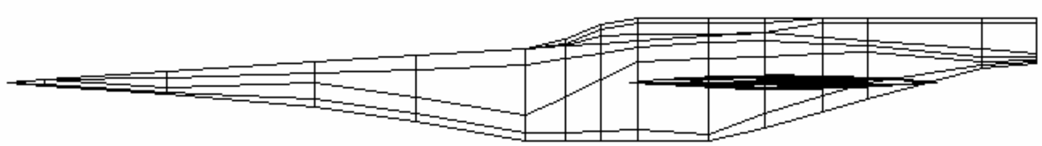


APAS Aerodynamics Model - Mated Configuration

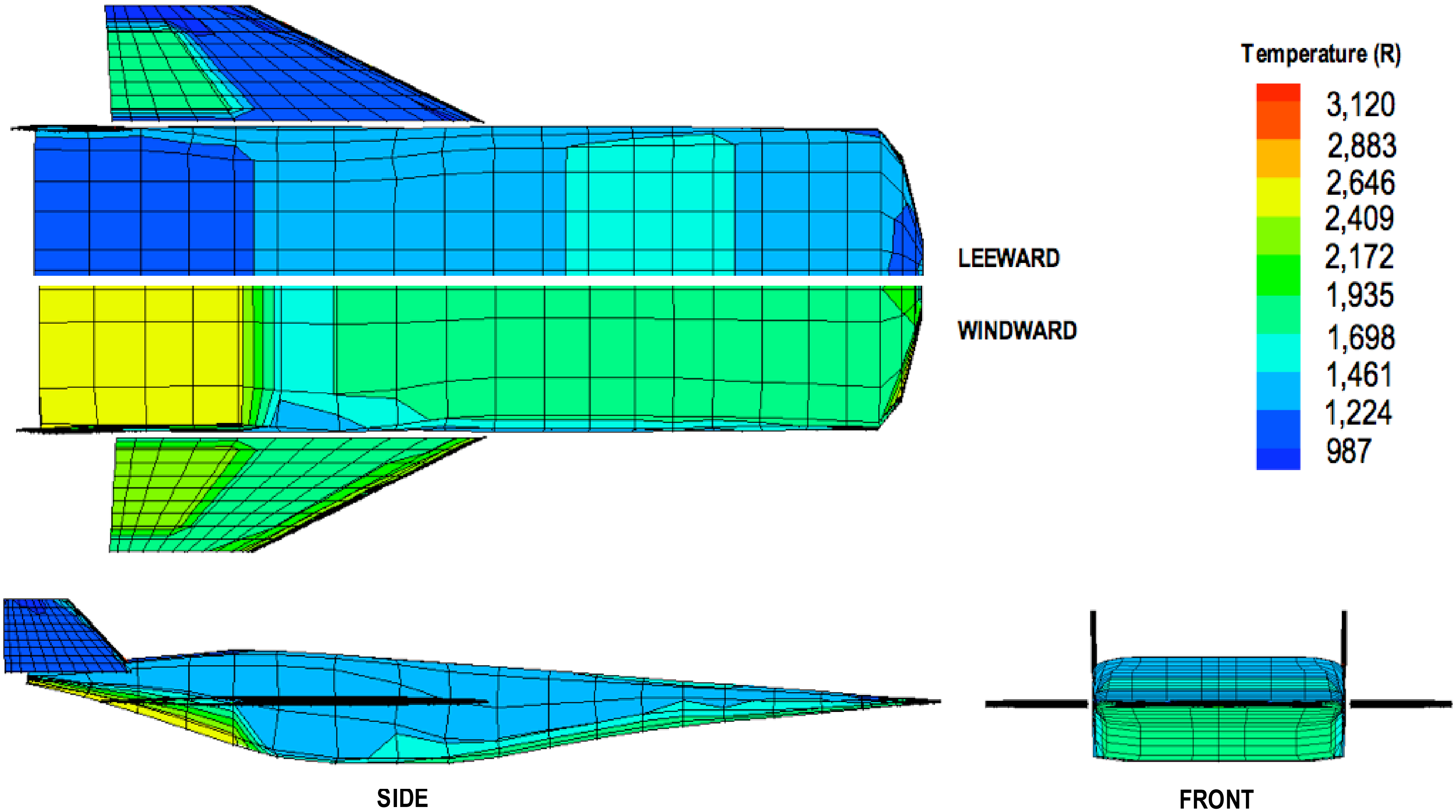








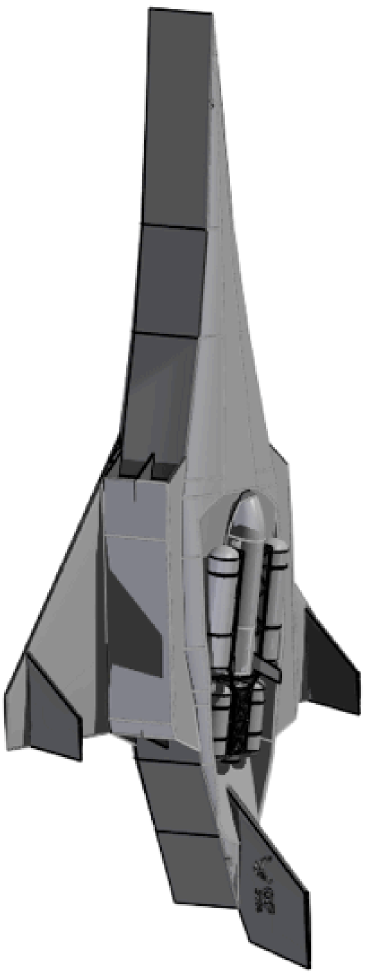
Quicksat Aeroheating Results - Maximum Surface Temperatures

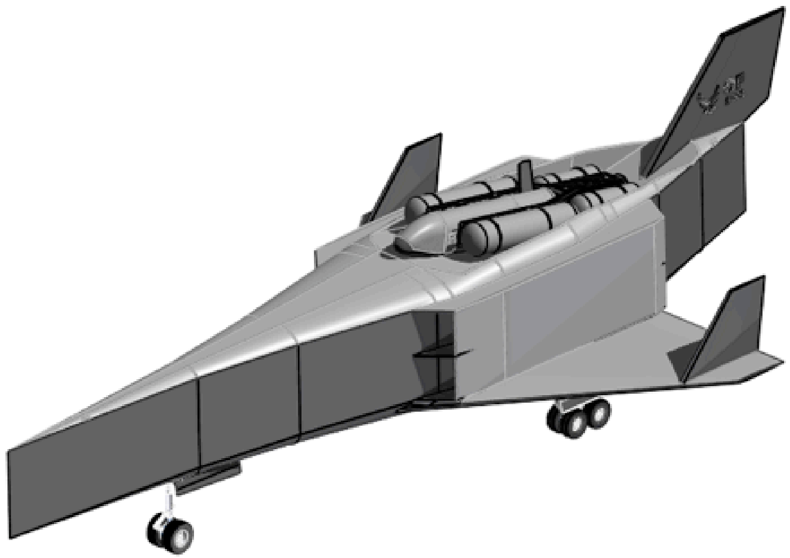


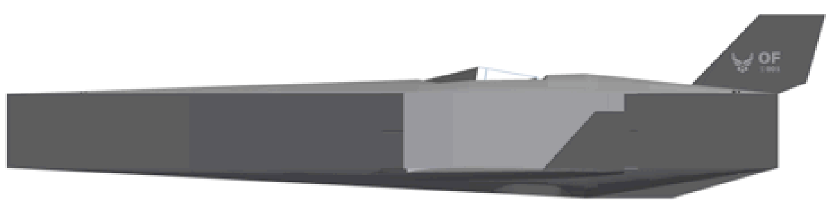
Sentinel TSTO MSP

Sentinel MSP

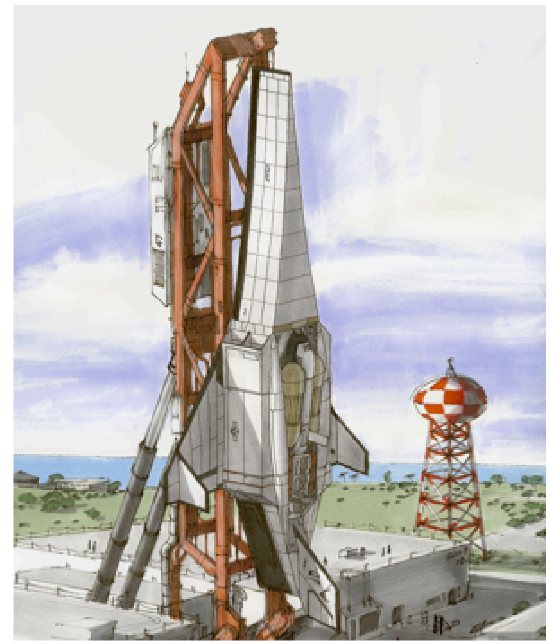
Space-Access Configuration

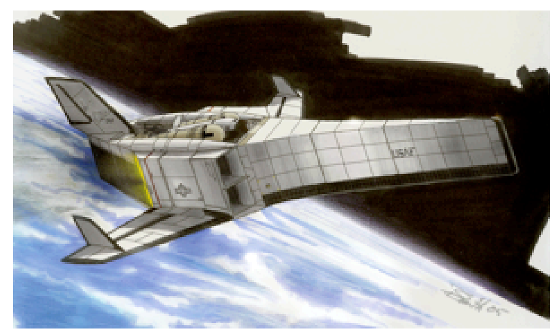


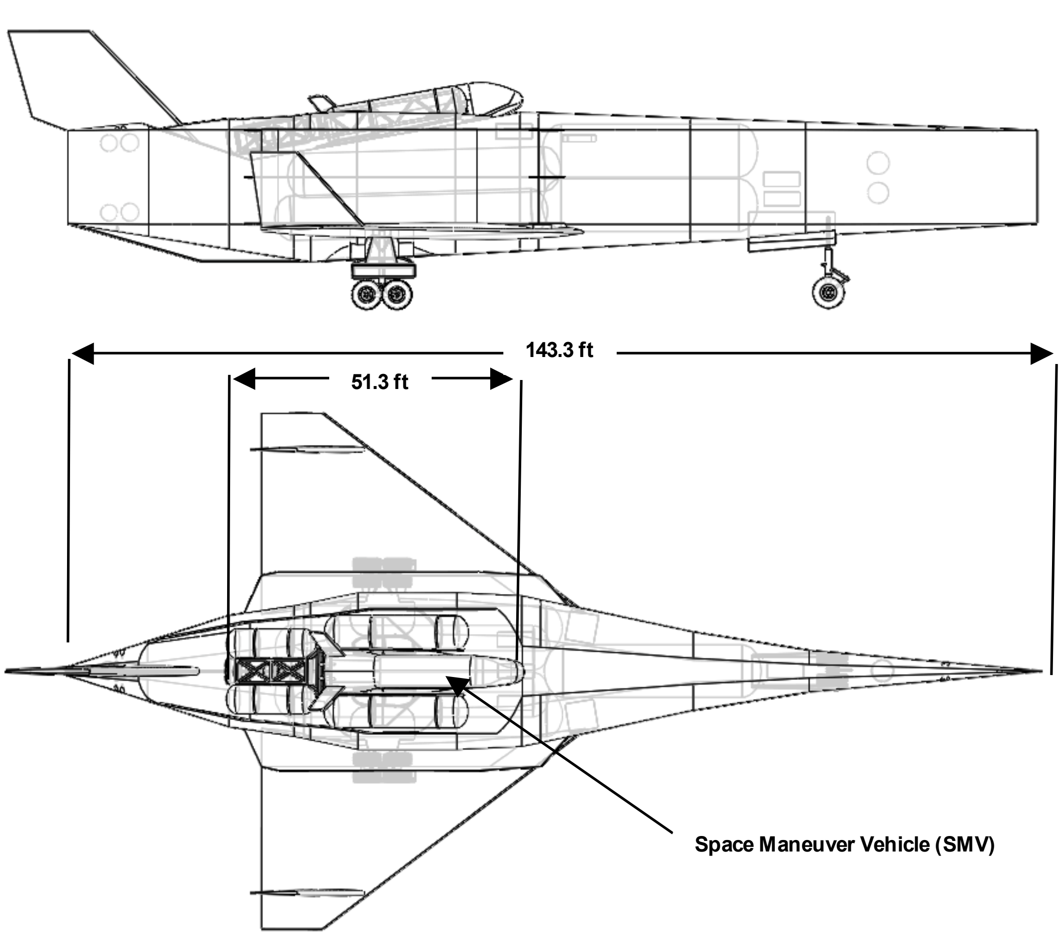


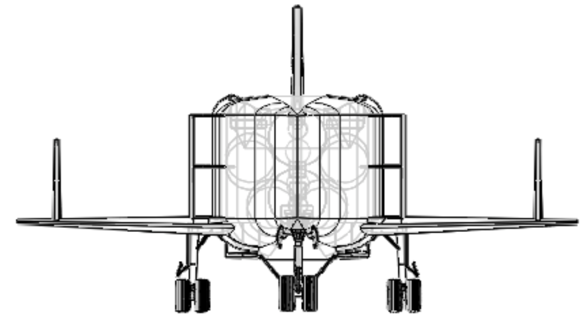


Liftoff from Military Space Port





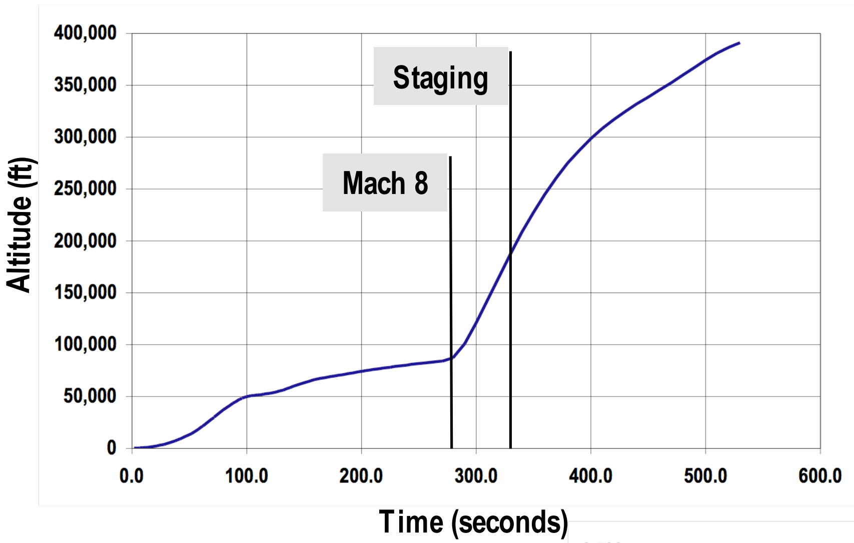


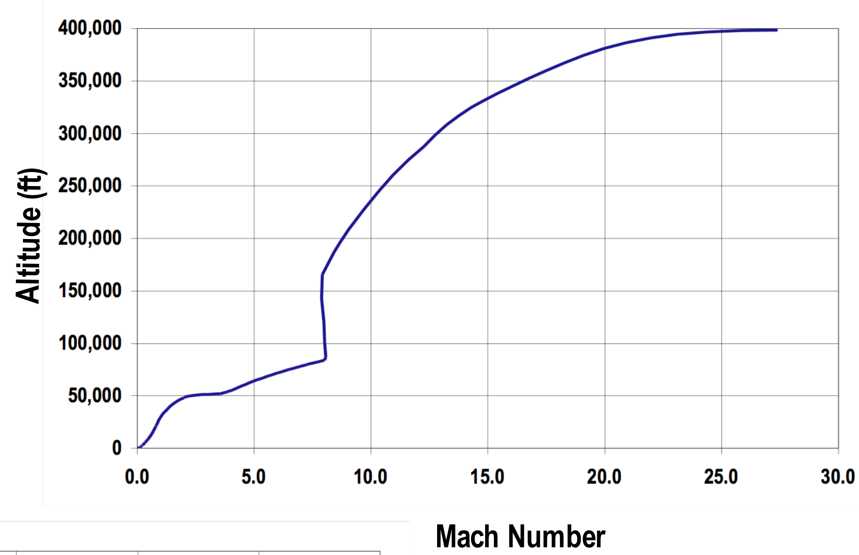


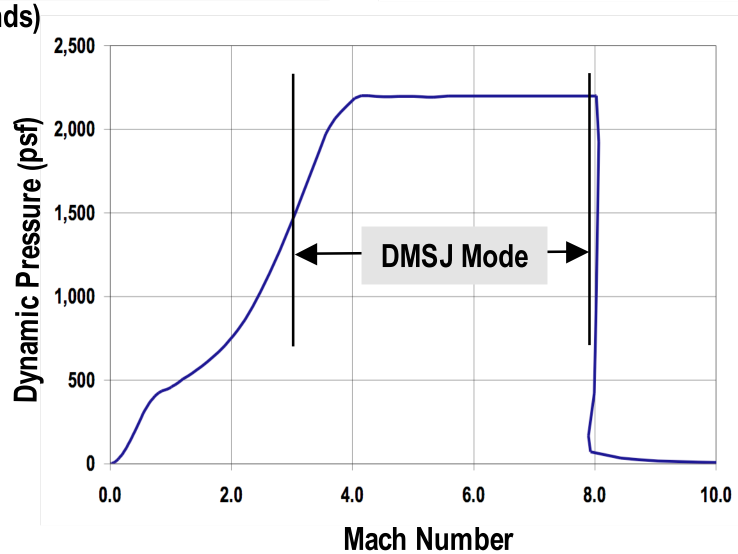
Gross Weight – system (lbs):	756,545
Dry Weight – *Sentinel* (lbs):	158,060
Dry Weight – Upperstage (lbs):	4,250
Mass Ratio – *Sentinel*:	2.638
Mixture Ratio – Sentinel:	1.185
Length (ft)	143.3
Booster Payload – Upperstage + SMV (lbs):	78,735
Space Maneuver Vehicle – SMV (lbs):	13,090

Integrated *Sentinel*/Upperstage MSP 3-View

Sentinel RBCC MSP - Ascent Trajectory Profiles







Disciplinary Analysis Tools

Quicksat and *Sentinel* Engineering Design Tools

Discipline	Tools, Models, Simulations
CAD and Packaging	Solid Edge
Aerodynamics	APAS, S/HABP, NASCART-GT (3-D CFD)
Propulsion	SRGULL, RJPA, NEPP, **REDTOP, REDTOP-2**, PARADIGM
Trajectory Optimization	**POST, POST-2, Flyback-Sim**
Aeroheating and TPS	**TPS-X, Sentry**
Weights and Sizing	**SEI-Sizer**
Subsystems	SESAW (avionics)
Operations	**AATe, FGOA**
Safety and Reliability	**GT-Safety II**
Economics and Cost	CABAM, **CABAM_A**, NAFCOM (2004, 2002)
System Engineering	**OptWorks, ProbWorks**, SAS JMP ModelCenter©, Analysis Server©

Vehicle Performance Toolsets (CAD and Packaging through Subsystems)

Economic Closure Toolsets (Operations through Economics and Cost)

Collaborative Design & Optimization (System Engineering)

■ = Wrapped for Closure in ModelCenter®

Non-Wrapped Analysis Tools

Aerodynamics
Tool(s): S/HABP with NASCART-GT CFD verification
Approach: Generated vehicle lift and drag coefficient (Cl and Cd) database and photographically scaled data.

Turbine Propulsion
Tool(s): NASA Engine Performance Program (NEPP)
Approach: Generated reference engine performance estimates (thrust and TSFC) and scaled with vehicle size. Engine weight derived from constant uninstalled T/W value.

Scramjet Propulsion
Tool(s): SRGULL
Approach: Fixed flowpath geometry and engine scaled with vehicle outer mold line. Engine weight based on panel unit weights (lbs/ft2) and turbomachinery/injectors sizing estimates that varied with fuel flowrate requirements.

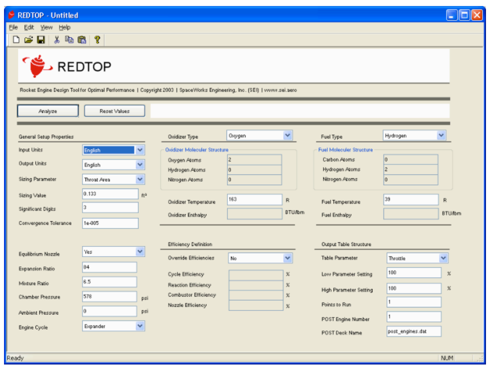
Solid Modeling
Tool(s): SolidEdge
Approach: Established reference vehicle for booster and upperstage (L=100 ft)

Photographically scaled OML and tracked packaging efficiency variation with size.

Subsystem: Avionics
Tool(s): SESAW
Approach: Curve fit results and inserted directly into Weights & Sizing model.

SpaceWorks Engineering, Inc. (SEI) introduces the Rocket Engine Design Tool for Optimal Performance (REDTOP), an analysis code for quick and accurate prediction of liquid propellant rocket engine performance. REDTOP features a Graphical User Interface (GUI) for operating the tool on the PC platform (Windows XP, 2000, NT, and ME).

For a user specified propellant combination (bi or mono-propellant), chamber pressure, nozzle expansion ratio, and mixture ratio, REDTOP will compute performance parameters such as: ideal, sea-level, vacuum and ambient thrust and specific impulse (Isp), nozzle throat and exit area, chamber temperature, nozzle exit pressure, and mass flow-rate. REDTOP features a number of sizing options for the engine. These include designing for a required thrust level (at a specified ambient condition), sizing at a specified total mass flow-rate, or designing for a specific throat area.



This package is currently available for purchase through individual licenses. The full product suite includes self-installing executable, documentation with case study examples, and selected online support. Free, two-year, site-wide university licenses are available.

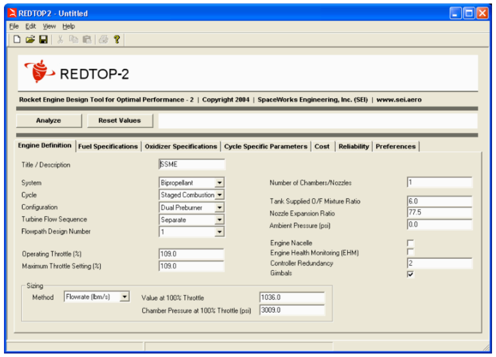
Liquid Rocket Performance: REDTOP

Built-in Oxidizer Propellant Options	Oxygen Nitrogen Tetraoxide (NTO) Hydrogen Peroxide (at various purity levels of 100% ,98% ,95% ,90% , and 85%)
Built-in Fuel Options	Hydrogen Methane Propane Octane RP/Kerosene Monomethyl Hydrazine (MMH) Unsymmetrical Dimethyl Hydrazaine (UDMH)
Other Propellant Options	Model generic fuel or oxidizer by specifying molecular structure and initial enthalpy
Built-in Engine Efficiency Database	Performance corrections based on engine cycle type (e.g. Expander vs. Gas Generator), nozzle flow losses, degree of reaction, and combustor efficiency, efficiency used to correct the theoretical (ideal) engine's performance
Throttled Engine Performance	User determined engine throttle range with new thrust, flow-rate, chamber pressure, and Isp

REDTOP Capabilities

^2

SpaceWorks Engineering, Inc. (SEI) introduces the Rocket Engine Design Tool for Optimal Performance (REDTOP)-2, an analysis code for the propulsion expert conducting conceptual and preliminary rocket engine design studies. REDTOP-2 features a Graphical User Interface (GUI) for operating the tool on the PC (Windows XP, 2000, NT, and ME) platform.



REDTOP-2 is capable of performing a steady-state engine power balance for a variety of cycles, predicting engine weight on a component basis, and computing the estimated development cost. REDTOP-2 allows for parametric engine design and sizing which include designing for a required thrust level (at a specified ambient condition), sizing at a specified total mass flow-rate, or designing for a specific throat area.

This package is currently available for purchase through individual licenses. The full product suite includes self-installing executable, documentation with case study examples, and selected online support.

Liquid Rocket Propulsion: REDTOP-2

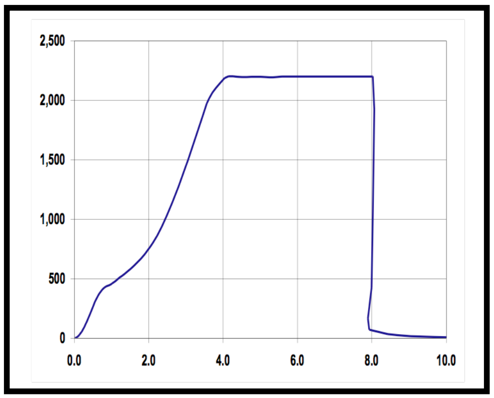
REDTOP-2 Capabilities

Built-in Oxidizer Propellant Options	Oxygen, Hydrogen Peroxide
Built-in Fuel Options	Hydrogen, Methane, Propane, Octane, RP/Kerosene
Generic Equilibrium Model	Can easily add new fuel, oxidizers, and product species by supplying simple property table of specific heat, enthalpy, density, and entropy versus temperature and pressure.
Cycle Options	Staged-Combustion, Gas Generator, Expander, and Tap-Off Fuel and/or Oxidizer-Rich Preburners Dual versus Single Preburner Series versus Parallel Turbine Flow
Throttled Engine Analysis	Will size engine at maximum operating condition to determine weight, then analyze at throttled engine setting for performance assessment.
Weight Breakdown Statement	Detailed weight predictions for chamber(s), nozzle(s), valves, low and high pressure pumps/turbines, controllers, etc.
Cost Modeling	2 Cost Model Options: 1) New engine development, 2) Existing engine modification. Computes DDT&E and first unit cost (TFU).

Primary Tool(s) - Program to Optimize Simulated Trajectories (POST & POST-2)

Description

- Three degree of freedom (3-DOF), untrimmed point mass simulation for ascent phase of booster and 2nd Stage. Simulation will determine optimal flight path to maximize insertion weight.
- Aerodynamics database and air-breathing propulsion data supplied as tables with multiple independent variables.
- Monitor vehicle angle-of-attack, dynamic pressure, Gs, normal force, and minimum engine throttle setting, with appropriate constraints imposed.



Ascent Trajectory

Primary Tool(s) - SEI In-House Flyback Simulator

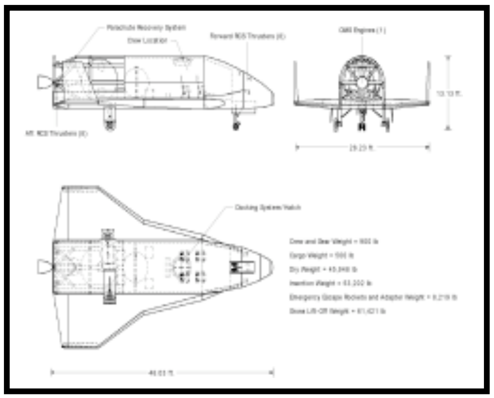
Description

- First-order C++ and spread-sheet model consisting of unpowered turn maneuver with descent to a cruise-back altitude and powered flyback. Execution times on order of a few seconds allows for in-the-loop analysis.
- User specifies vehicle data (weight, Sref, etc.), aerodynamic database, propulsion systen Isp, cruise Mach number and cruise Altitude.

Booster Flyback

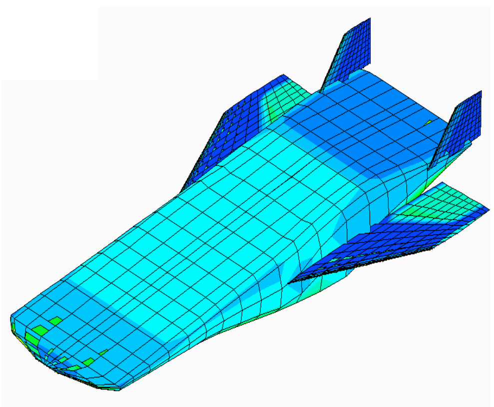
Primary Tool(s)
- MER Database, higher-order analysis

Description
- For Booster
  - Iterative sizing model based on photographic vehicle scaling about an as-drawn configuration. Internal packaging efficiency is function of vehicle size.
  - Combination of 'historical' MERs, physics based models, and results from higher-fidelity tools
- For 2nd Stage
  - Iterative sizing model based on varying total propellants onboard.
  - Combination of 'historical' MERs, physics based models, and results from higher-fidelity tools
- Excel© Solver utilized to target required mass ratios.
- 15% dry-weight margin applied to both stages, not including propellant reserves, residuals, and unusables.



Weights and Sizing (W&S)

Aeroheating and TPS Sizing: Sentry



- 1-D passive TPS sizing tool developed by SpaceWorks Engineering, Inc
- Written in C++ code with command line execution on PC, Mac OS X, and SGI machines
- Execution times on the order of a few minutes (2-10)
- Uses POST or OTIS trajectory data for ascent profile (time, velocity, AOA, etc.)
- Utilizes S/HABP code for geometry and convective heating data
- Dynamic memory allocation in code allows for unrestricted problem size
- Tool selects minimum weight TPS tile from database of stackup options
- Easily wrapped in ModelCenter© for incorporation in design iteration
- Can be used as standalone TPS analysis tool for single stackup/point assessment
- User can exclude analysis at any identified body panel (e.g. propulsive flowfield on an aftbody)
- Supports analysis of segmented trajectory simulations (e.g. flyout followed by flyback)
- Candidate regions for use of active-TPS methods (cooled or ablative) identified but not analyzed

High-Fidelity Closure Model

ModelCenter© Collaborative Environment

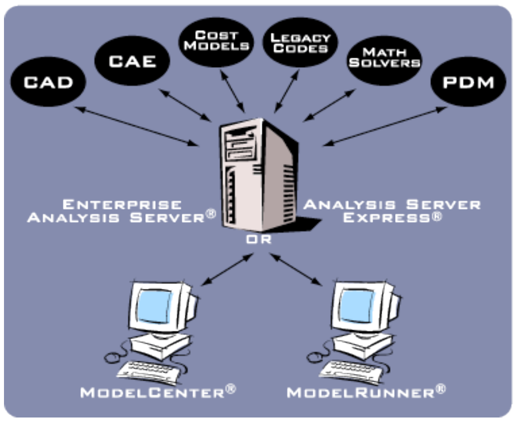
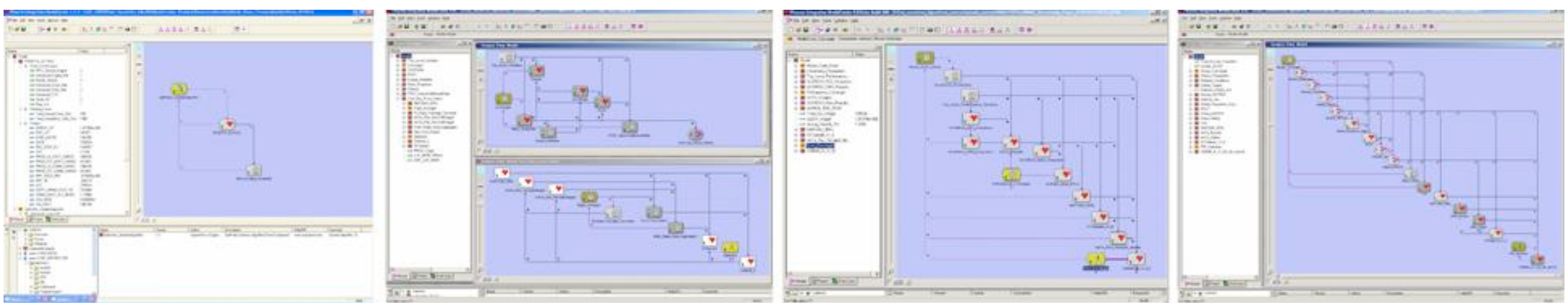


Image Source: Phoenix Integration Inc.
http://www.phoenix-int.com/products/index.html

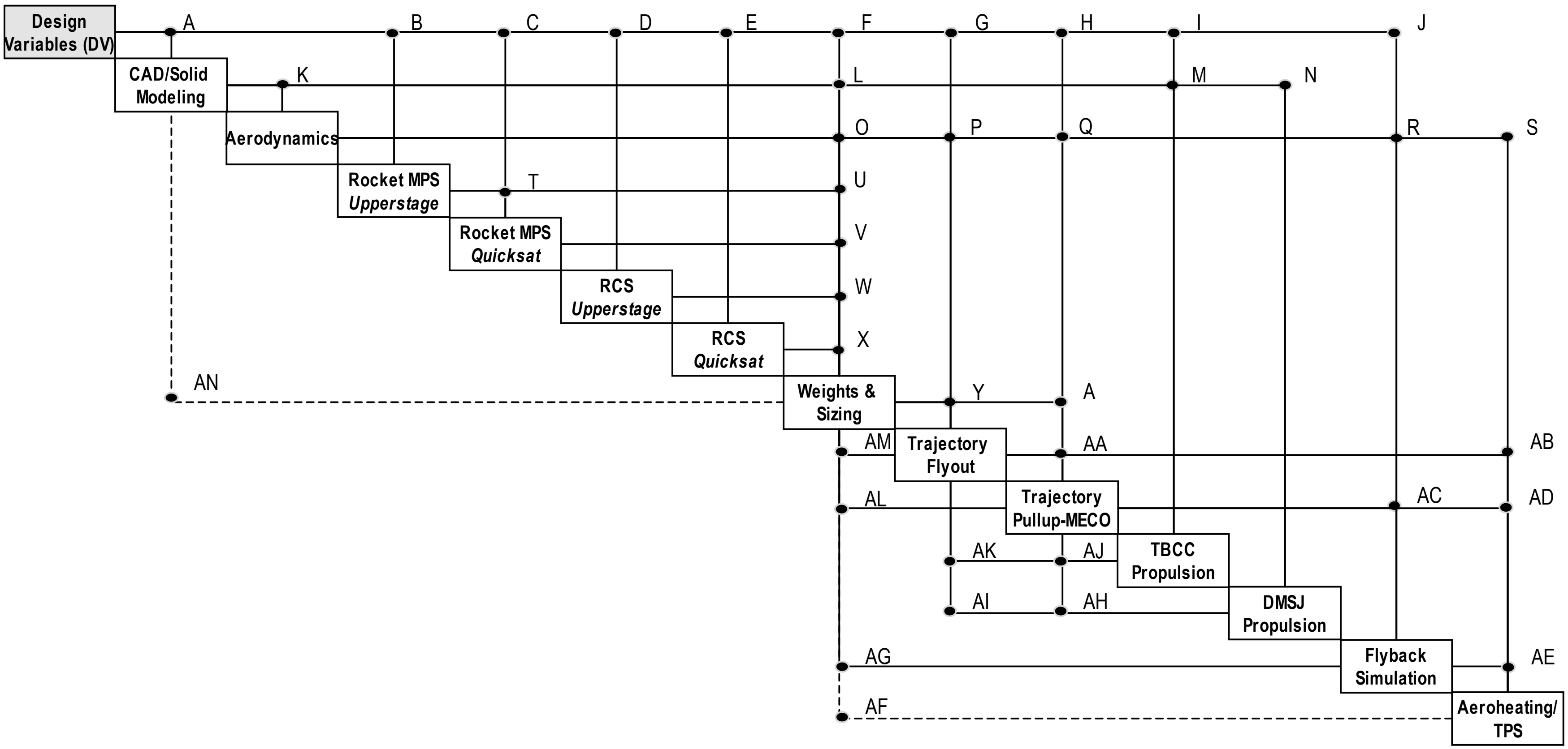
"Phoenix Integration allows manufacturing companies to integrate and automate numerous software tools, remote locations, and different computing platforms into a cohesive environment for systems design…

…Our client software and back-end server software products help you build an integrated process for your engineering design team."

Phoenix Integration Inc.
http://www.phoenix-int.com



Quicksat/Upperstage Design Structure Matrix (DSM): Performance Closure Process



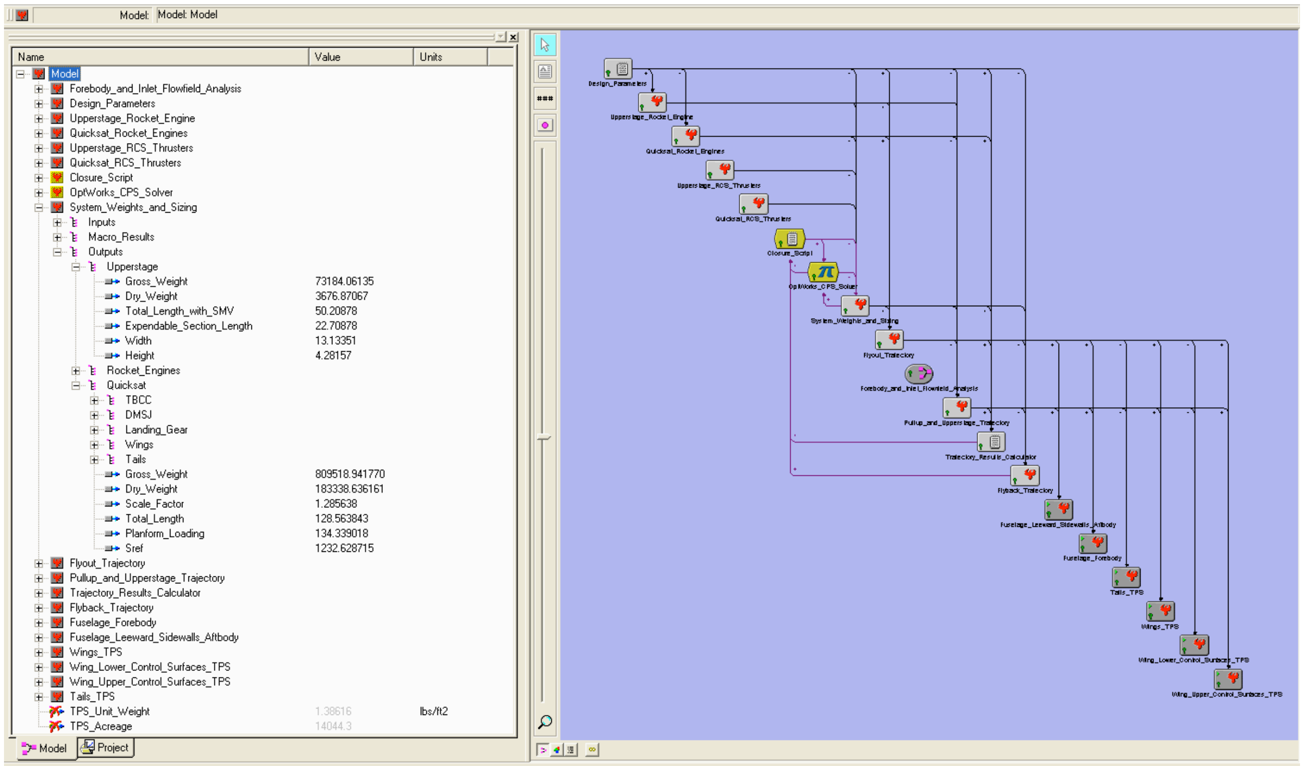
- - - - - - Indicates weak coupling

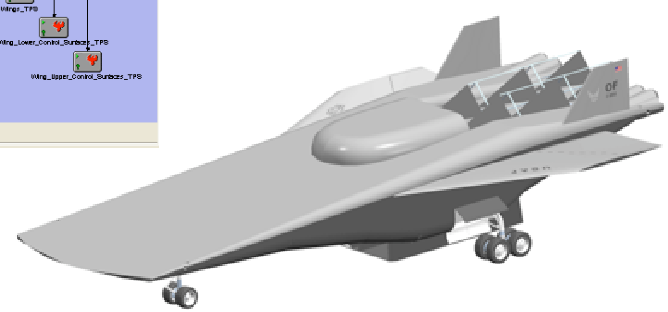
Vehicle Closure Process

- Wrapped components brought into ModelCenter® and linked together
  - Approximate Setup Time: 1-2 weeks
- Utilized Fixed-Point Iteration (FPI) technique for iterating and converging design
- Established 'Inner' and 'Outer' FPI loops
  - Inner loop for faster, tightly coupled analysis
  - Outer loop incorporated TPS analysis (slower analysis with only small changes in results)
- Single-point vehicle design closure requires approximately 2-3 Outer-loop iterations each with 8-10 Inner-loop iterations
  - Single inner-loop iteration takes 5-10 minutes
  - Single outer-loop iteration requires about 45 minutes
- Trajectory analysis split into multiple phases (booster ascent, booster pullup, upperstage to MECO, etc..)
- After POST/POST-2 trajectory analysis complete, a tabular results file containing Mach number, velocity, altitude, and AOA vs. Flight Time passed to Sentry analysis components (cross-platform file transfer for *Quicksat*, SGI to Mac)
- ModelCenter stores (copy) all vehicle information from disciplinary analysis
  - POST and POST-2 Input and Output Files
  - REDTOP-2 power balance and engine weight estimation results
  - TPS results for fuselage, wings, tails, verticals, and control surfaces

Quicksat/Upperstage Closure Model within ModelCenter© Environment

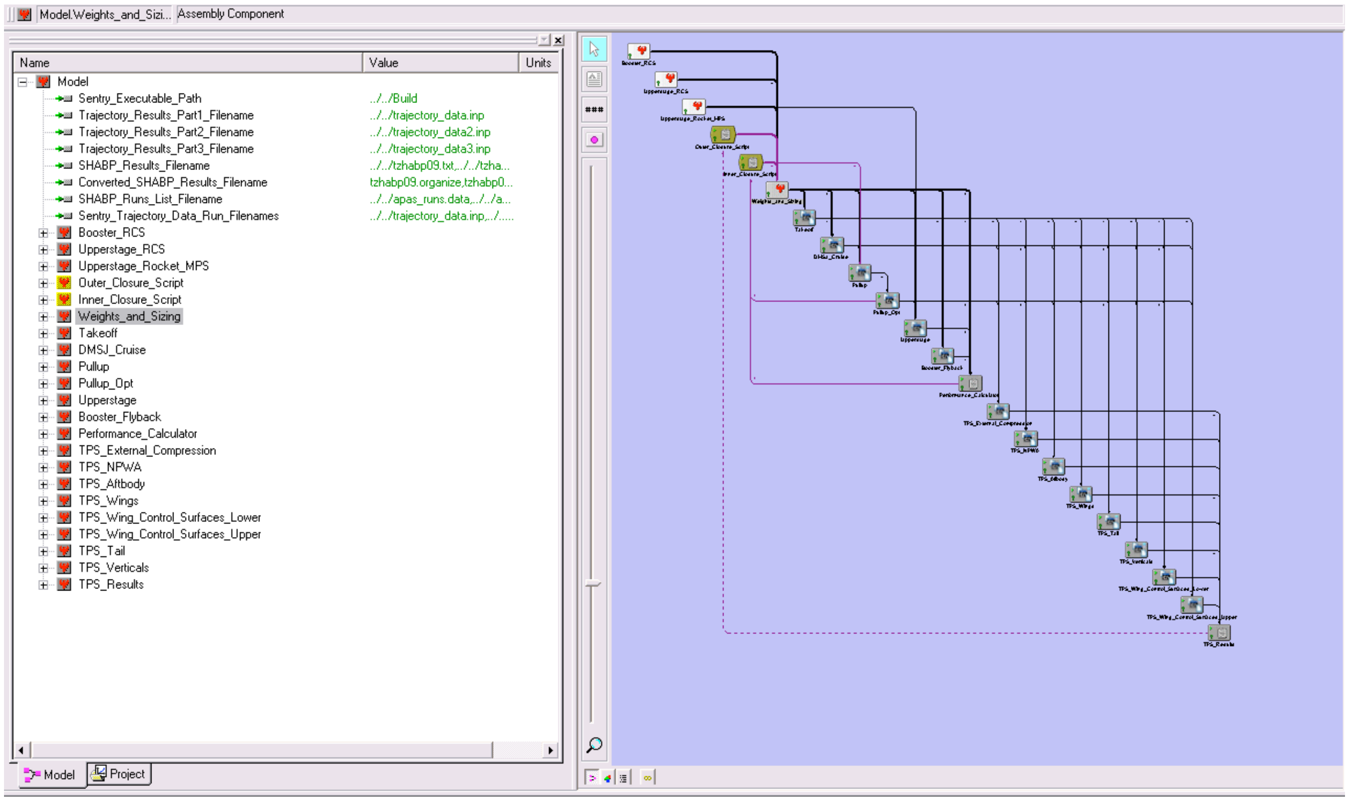
Analysis being performed on multiple machines, including: PIV Dell PC, dual-processor 2.0GHz Mac G5, PC Server, SGI Octane, and PIII Dell Laptop

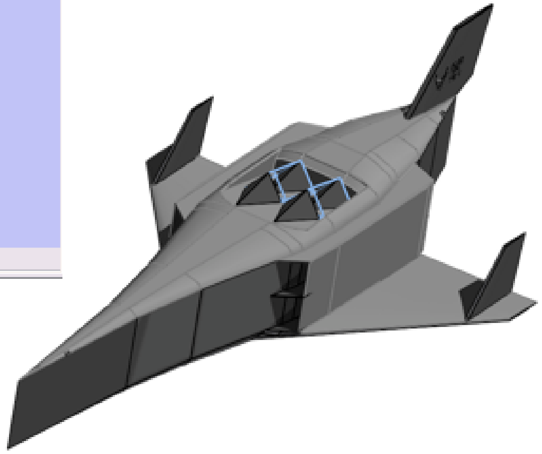




Sentinel/Upperstage Closure Model within ModelCenter© Environment

Analysis being performed on multiple machines, including: Dell PC with dual-Xeon processors and 64-bit Mac G5 with dual-2.0GHz





Model Capabilities

- Vehicle closure models require up-front investment in process design and setup

  …This expense is more than made up by benefits and future time savings

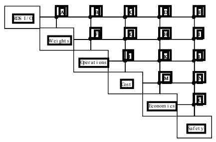
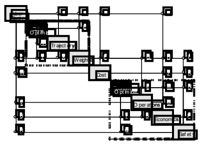
- Closure models for both systems has enabled a variety of trade studies to be conducted quickly
  - Staging Mach Number
  - DMSJ Pullup Mach Number
  - Engine T/W Sensitivity
  - Alternate Propellant Options

- Users have been able to conduct a number of one-variable at a time optimzations and sensitivity analysis
  - Rocket engine chamber pressure and expansion ratio
  - Tail-rocket ignition through transonic on *Quicksat*
  - RBCC IRS-mode shut-down condition on *Sentinel*

- Process is repeatable
- Process avoids transcription errors during data exchange

ROSETTA Meta-Model

Engineering Integration and Optimization Frameworks

	ROSETTA Model	ModelCenter© and Analysis Server ©
		
Source	SEI developed Reduced Order Simulation for Evaluating Technologies and Transportation Architectures (ROSETTA)	Suite of tools from Phoenix Integration©
About	Spreadsheet-based meta-model is a representation of the design process for specific architectures	Collaborative engineering framew ork
Foundation	Based upon higher fidelity models and simulations and refined through updates from such models	Actual models and simulations are used in a standardized GUI
Enables	Rapid probabilistic assessments	Netw orked, design process automation Simultaneous, multi-platform analyses Trade study and optimization options

ROSETTA Model Introduction

- Reduced Order Simulation for Evaluation of Technologies and Transportation Architectures (ROSETTA)
  - A spreadsheet-based meta-model that is a representation of the design process for a specific architecture (ETO, in-space LEO-GEO, HEDS, etc.)
  - Each traditional design discipline is represented as a contributing analysis in the Design Structure Matrix (DSM)
  - Based upon higher fidelity models (i.e. POST, APAS, CONSIZ, etc.) and refined through updates from such models
  - **Based upon an existing, reference baseline design**
  - Can be used deterministically to examine design space of that baseline
  - Executes each architecture simulation in only a few seconds
    - Requirement for uncertainty analysis through Monte-Carlo simulation
  - Architectures are modified through Design Influence Factors (DIFs) that can be broken out:
    - **PIFs: Programmatic Influence Factors (i.e. govt. contribution, market growth, etc.)**
    - **VIFs: Vehicle Influence Factors (i.e. Isp, wing weight, T/We, cost, etc.)**
  - Outputs measure progress towards customer goals (mission capture rate, life cycle cost, safety, etc.)
    - Standard deterministic outputs as well as probabilistic through Monte Carlo simulation

ROSETTA models contain **representations** of the full design process.
Individual developer of each ROSETTA model determines **depth** and **breadth** of appropriate contributing analyses.
More assumptions, fewer DSM links than higher fidelity models due to need for faster calculation speeds.

Monte Carlo	Performs Monte Carlo uncertainty simulation using random variables by placing distributions (normal, triangular, Weibull, etc.) on inputs. Generates output statistics for the forecast variables (average, mean, certainty level, etc.) even as simulation is running.
DPOMD	Implements the Discrete Probability Optimal Matching Distribution (DPOMD) technique that serves as an efficient alternative to direct Monte Carlo simulation for certain classes of problems. Allows estimation of a probabilistic output distribution with a small number of runs.
Pareto Sensitivity	Determines the contribution or sensitivity of each selected input with respect to each selected output with appropriate ranking of contribution.
RSE Generator	Produces polynomial regression equations to approximate more complex or time-consuming components enabling faster execution of probabilistic techniques such as Monte Carlo. Generates output statistics on goodness of fit to selected data. Enables subsequent use of regression coefficients.

ProbWorks Suite of Components
(www.piblue.com)

ROSETTA Model Implementation Summary

- The ROSETTA spreadsheet model for the *Sentinel* MSP concept is MS Excel based
  - 20 worksheets of varying fidelity encompassing performance and metrics assessment
  - ~1.3 MB MS Excel workbook
  - Several VBA functions and subroutines
  - Specific performance convergence subroutine must run to converge vehicle
  - Model execution on a Pentium 1.7 GHz with 1 GB RAM running MS Office 2003 is under 10 seconds

- Any changes of the PIFs and VIFs result in the concept needing to be reconverged both physically (through vehicle lengths, propellant loads, etc.) and those results propagated through to the cost, S/R, and operations models

- Primary user interaction will be through 'Inputs' and 'Outputs' worksheets
  - Additional results data and model manipulation can be accessed in disciplinary sub-worksheets

- Performance Closure
  - Enabled through short-cut keys 'Ctrl+u'
  - Convergence utilized Excel© Solver optimizer
  - Macro procedure:
    - (1) Vary propellant load on upperstage to achieve mass ratio required from trajectory analysis
    - (2) Vary booster length to achieve required mass ratio (and mixture ratio) from trajectory analysis
    - (3) Life-Cycle analysis models execute automatically

    Execution Time: 10 seconds

- Disciplinary Analysis
  - Response Surface Models:
    - Ascent Trajectory (POST-2), Upperstage Propulsion (REDTOP-2), Flyback Trajectory(Flyback-Sim)
    - Ascent trajectory split into two phases: (i) liftoff to Mach 6, (ii) Mach 6 to pullup Mach number and staging
  - Reduced Order Models:
    - RDT&E (NAFCOM-2004)
  - Full Models:
    - Weight and Sizing, FGOA, AATe, GT-SafetyII (all spreadsheet based tools)

ROSETTA Model: INPUTS

REDUCED ORDER SIMULATION FOR EVALUATING TECHNOLOGIES AND TRANSPORTATION ARCHITECTURES (ROSETTA)

I. INPUTS

Discipline	Inputs
Model Basis	Meta-model of a Two Stage to Orbit (TSTO) Military Space Plane (MSP): *Sentinel* with expendable upperstage
ROSETTA Model Version No.	1.16.III
Revision Date	10/13/2005
Revising Organization	SpaceWorks Engineering, Inc. (SEI) | www.sei.aero
Organizational Contact	Dr. John E. Bradford | john.bradford@sei.aero

Comments:
* -

Text Color Code:

Red	User or Optimizer Inputs
Purple	Solver Convergence Parameters
Blue	Outputs
Black	Calculations

I.1 Mission Parameters

Level 1	Level 2	Parameter Name	Value	Units	Min Value	Max Value
Space Access						
	SMV Delivery					
		Launch Site Latitude	28.5	deg	0.0	90.0
		Payload Weight	13090.0	lbs	0.0	25000.0
		Payload Length	27.5	ft	0.0	50.0
		Orbital Inclination	28.5	deg	0.0	90.0
		Apogee	197.0	nmi	100.0	400.0
		Perigee	70.0	nmi	30.0	400.0
		Circularize Payload	No			
Hypersonic Strike						
		Number ECAVs	4		1	10
		ECAV Weight (each)	2000.0	lbs	500.0	3000.0
		ECAV Range after High-Speed Release	1500.0	nmi	250.0	5000
		Flyback Propellant Fraction Used for Flyout	66.7%		0.0	1.0
		Flyout DMSJ Isp	1200.0	s	500.0	3000.0

I.2 Sentinel Booster Parameters

Level 1	Level 2	Parameter Name	Value	Units	Min Value	Max Value
Fluids						
	Oxidizer					
		Cryogenic	Yes			
		Density	71.2	lbs/ft3	50.0	120.0
		MPS Reserves	0.75%		0.0	2.0
		MPS Residuals	0.20%		0.0	2.0
	Fuel					
		Cryogenic	No			
		Density	50.3	lbs/ft3	30.0	60.0
		MPS Reserves	0.75%		0.0	2.0
		MPS Residuals	0.20%		0.0	2.0
Propulsion						
	RBCC IRS Mode					

ROSETTA Model: OUTPUTS

REDUCED ORDER SIMULATION FOR EVALUATING TECHNOLOGIES AND TRANSPORTATION ARCHITECTURES (ROSETTA)

II. OUTPUTS

Discipline	Outputs
Model Basis	Meta-model of a Two Stage to Orbit (TSTO) Military Space Plane (MSP): Sentinel with expendable upperstage
ROSETTA Model Version No.	1.16.III
Revision Date	10/13/2005
Revising Organization	SpaceWorks Engineering, Inc. (SEI) | www.sei.aero
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Comments:
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Text Color Code:

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Purple	Solver Convergence Parameters
Blue	Outputs
Black	Calculations

II.1 *Sentinel*

Level 1	Level 2	Parameter Name	Value	Units	Comments
Space Access					
	SMV Delivery				
		GLOW	770,532.3	lbs	
		Booster Dry Weight	160,252.8	lbs	
		Length (nose-to-tail)	144.2	ft	
		Fuselage Height	13.8	ft	
		Vehicle Wing Span	76.3	ft	
		Theoretical Sref	2571.2	ft2	
		Reference Vehicle Scale Factor	1.0681	L/Lref	
		Booster Ascent Mass Ratio	2.640		
		Booster Ascent Mixture Ratio	1.191		oxidizer-to-fuel ratio by weight
		Booster Overall Mixture Ratio (Ascent+Flyback)	0.969		oxidizer-to-fuel ratio by weight
		Downrange Distance	339.24	nmi.	distance to staging point
		Booster Flyback Mass Ratio	1.118		
		RBCC SLS Thrust (total)	957,555.5	lbs	
		RBCC Inlet Width	6.41	ft	
		RBCC Inlet Height	3.31	ft	
		RBCC Installed T/W (SLS)	23.48		uninstalled + feed lines/purge lines/etc.
		RBCC Thruster (per engine, to epsilon=10)-			
		Mass Flowrate	627.4	lbm/s	
		Vacuum Thrust	197748.6	lbs	
		SLS Thrust	192230.9	lbs	
		Vacuum Isp	315.2	s	
		SLS Isp	306.4	s	
		Exit Area	2.61	ft2	
Hypersonic Stike					
		Conformal Tank Weight	1606.7	lbs	
		Total Strike Range	3780.7	nmi	
		Available Propellants	87957.9	lbs	
		Available Flyout Propellants	19177.4	lbs	

Inputs | Outputs | Performance | Prop-Upperstage Rocket | W&S-Upperstage | W&S-Upperstage-WBS | Traj-Upperstage SMV | W&S-Booster | W&S-Booster WBS | Traj-Ascent-Flyout | Traj-

ROSETTA Model:
PERFORMANCE CLOSURE

REDUCED ORDER SIMULATION FOR EVALUATING TECHNOLOGIES AND TRANSPORTATION ARCHITECTURES (ROSETTA)

III. PERFORMANCE

Discipline	Performance Convergence (Requires VBA Macro Initiation, through control button below or CTRL + U)
Model Basis	Meta-model of a Two Stage to Orbit (TSTO) Military Space Plane (MSP): Sentinel with expendable upperstage
ROSETTA Model Version No.	1.16.III
Revision Date	10/13/2005
Revising Organization	SpaceWorks Engineering, Inc. (SEI) | www.sei.aero
Organizational Contact	Dr. John E. Bradford | john.bradford@sei.aero

Comments:
* - NOTE: CTRL+u = Runs Performance Convergence

Text Color Code:

Red	User or Optimizer Inputs
Purple	Solver Convergence Parameters
Blue	Outputs
Black	Calculations

III.1 Sentinel Performance Calculation Parameters

Level 1	Parameter Name	Value	Units	Comments
Sizing Outputs				
	System GLOW	770,532.3	lbs	
	Sentinel Dry Weight	160,252.8	lbs	
Sizing Parameter				
	Vehicle Length	144.187	ft	
Objective				
	Mass Ratio Required	2.64016		
	Mass Ratio Available	2.64015		
	Mass Ratio Difference	0.000		Goal: Minimize

III.2 Upperstage Performance Calculation Parameters

Level 1	Parameter Name	Value	Units	Comments
Sizing Outputs				
	Upperstage GLOW	78,592.3	lbs	
	Upperstage Dry Weight	4,255.2	lbs	
Sizing Parameter				
	Ascent Propellants	61,840.3	lbs	
Objective				
	Mass Ratio Required	4.115		
	Mass Ratio Available	4.115		
	Mass Ratio Difference	0.000		Goal: Minimize

ROSETTA vs. High Fidelity Verification Runs

Baseline System
Mach 8 pullup, Staging at 9,000 fps, RBCC Engine T/W=27)

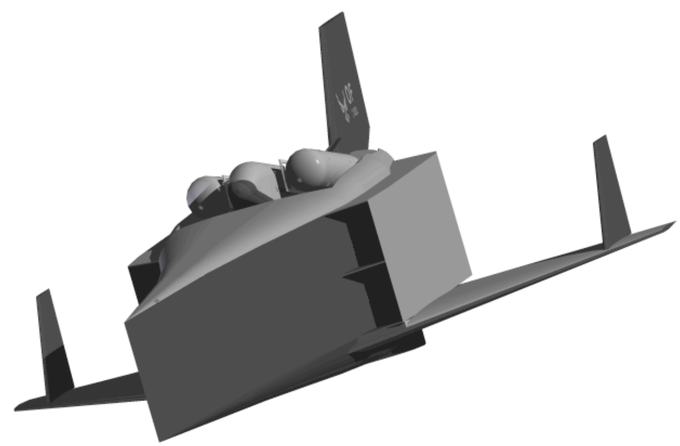
Component	High-Fidelity Closure	ROSETTA
System GLOW (lbs)	756,011	756,545
Sentinel Dry Weight (lbs)	157,998	158,060
Upperstage GLOW (lbs)	78,592	78,735
Upperstage Dry Weight (lbs)	4,255	4,250
Vehicle Length (ft)	143.3	143.3

Test Case #1
Mach 8 pullup, Staging at 10,000 fps, RBCC Engine T/W=27)

Component	High-Fidelity Closure	ROSETTA
System GLOW (lbs)	888,397	886,586
Sentinel Dry Weight (lbs)	181,613	181,231
Upperstage GLOW (lbs)	68,802	69,036
Upperstage Dry Weight (lbs)	3,818	3,817
Vehicle Length (ft)	153.5	153.3

Test Case #2
Mach 7 pullup, Staging at 9,000 fps, RBCC Engine T/W=32)

Component	High-Fidelity Closure	ROSETTA
System GLOW (lbs)	737,309	740,132
Sentinel Dry Weight (lbs)	148,177	148,627
Upperstage GLOW (lbs)	78,592	78,721
Upperstage Dry Weight (lbs)	4,255	4,247
Vehicle Length (ft)	142.4	142.5



Sentinel ROSETTA Model in ModelCenter©

Sample Probability Analysis

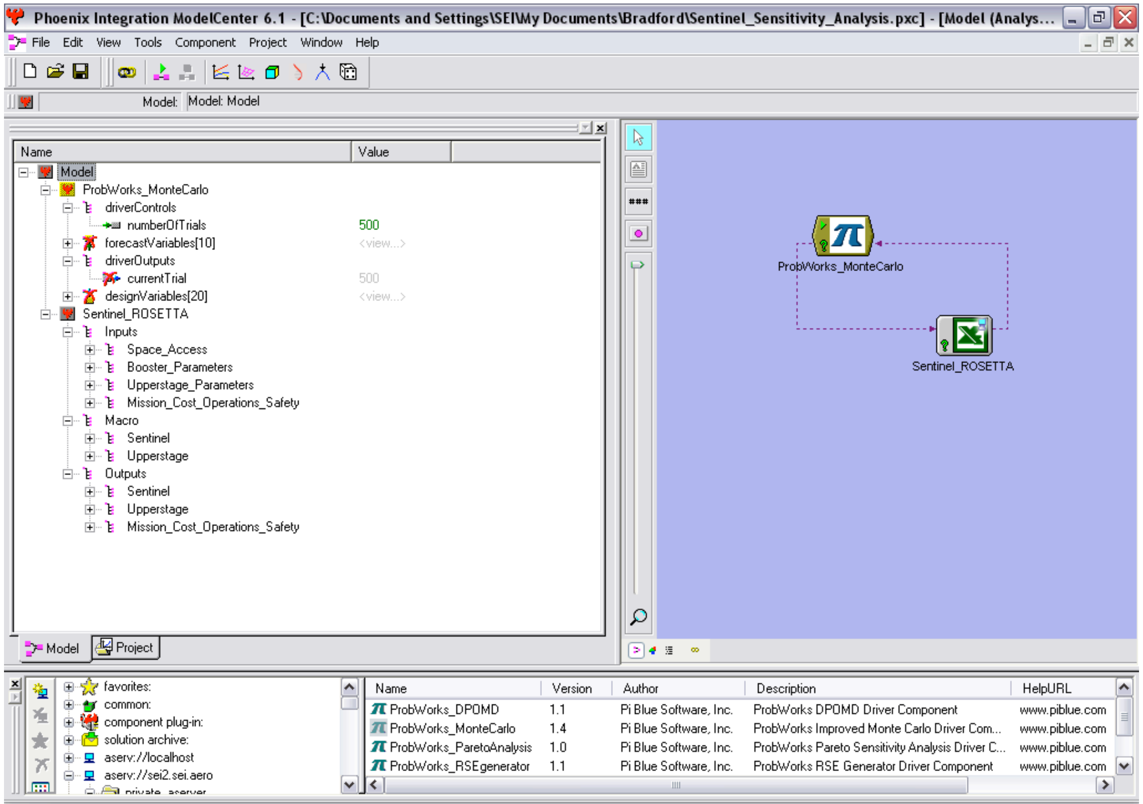
Placed triangular distributions on *Sentinel* and Upperstage hardware WBS Items

Subsystem weight multipliers ranged from 0.8 to 1.2 on major groups (wing/body/tail), to 0.1-3.0 for smaller subsystems (avionics/ACS/etc.)

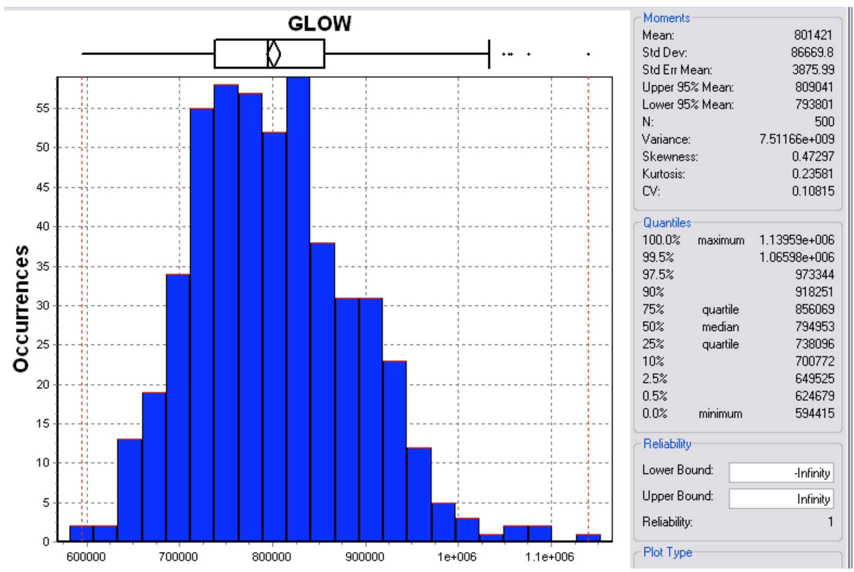
Ran 500 Monte Carlo Simulations (=500 closed vehicle designs)

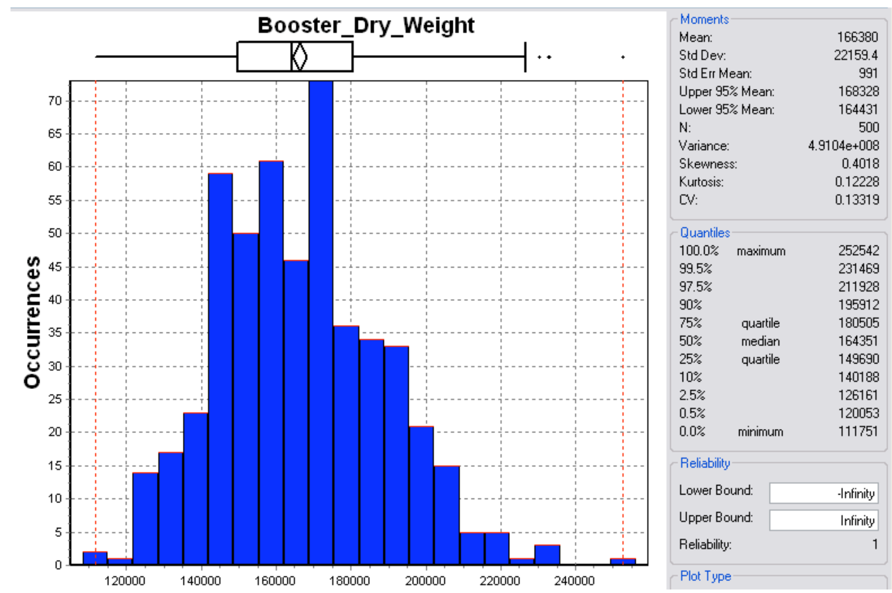
Tracked system GLOW, booster dry weight, upperstage GLOW, and upperstage dry weight

Approximate run time: 4 hours



Probabilistic Analysis Results #1: System GLOW and Booster Dry Weight PDFs

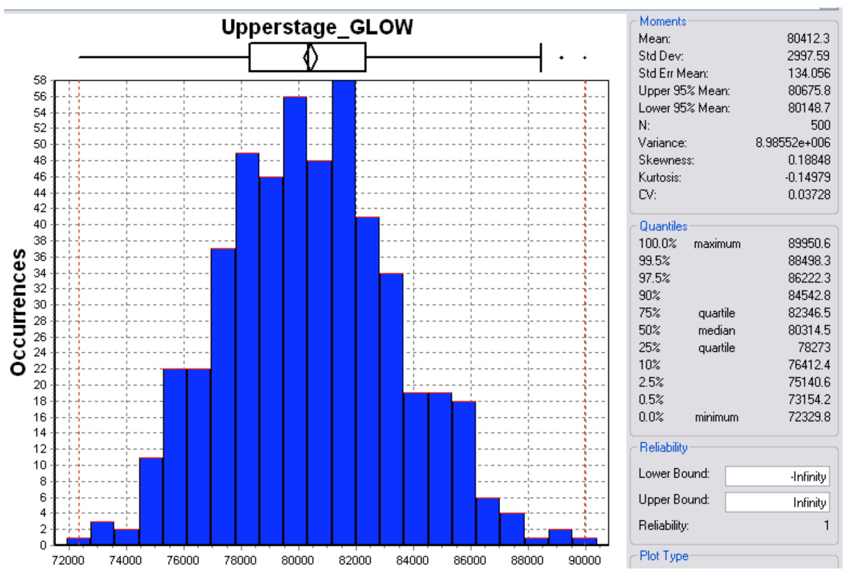


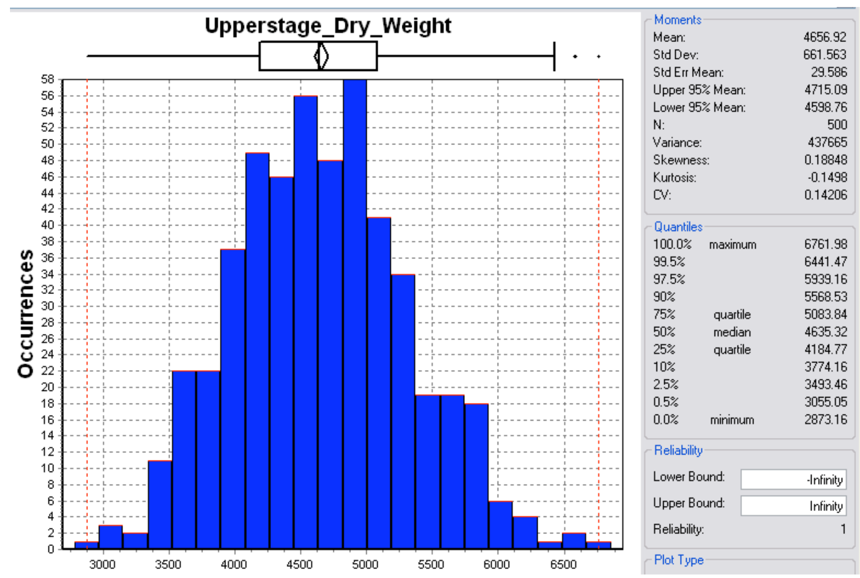


- System GLOW varied from minimum of 600Klbs to maximum of 1.1Mlbs
- 90% Confidence Value is 918,251 lbs (*90% of all simulations resulted in GLOW < 918,251 lbs*)

- Booster dry weight varied from minimum of 120Klbs to maximum of 240Klbs
- 90% Confidence Value is 195,912 lbs (*90% of all simulations resulted in dry weight < 195,912 lbs*

Probabilistic Analysis Results #2: Upperstage GLOW and Dry Weight PDFs





- Upperstage GLOW varied from minimum of 72Klbs to maximum of 90Klbs
- 90% Confidence Value is 84,543 lbs (*90% of all simulations resulted in GLOW < 84,543 lbs*)

- Upperstage dry weight varied from minimum of 3Klbs to maximum of 6.5Klbs
- 90% Confidence Value is 5,568 lbs (*90% of all simulations resulted in dry weight < 5,568 lbs*

Summary and Conclusions

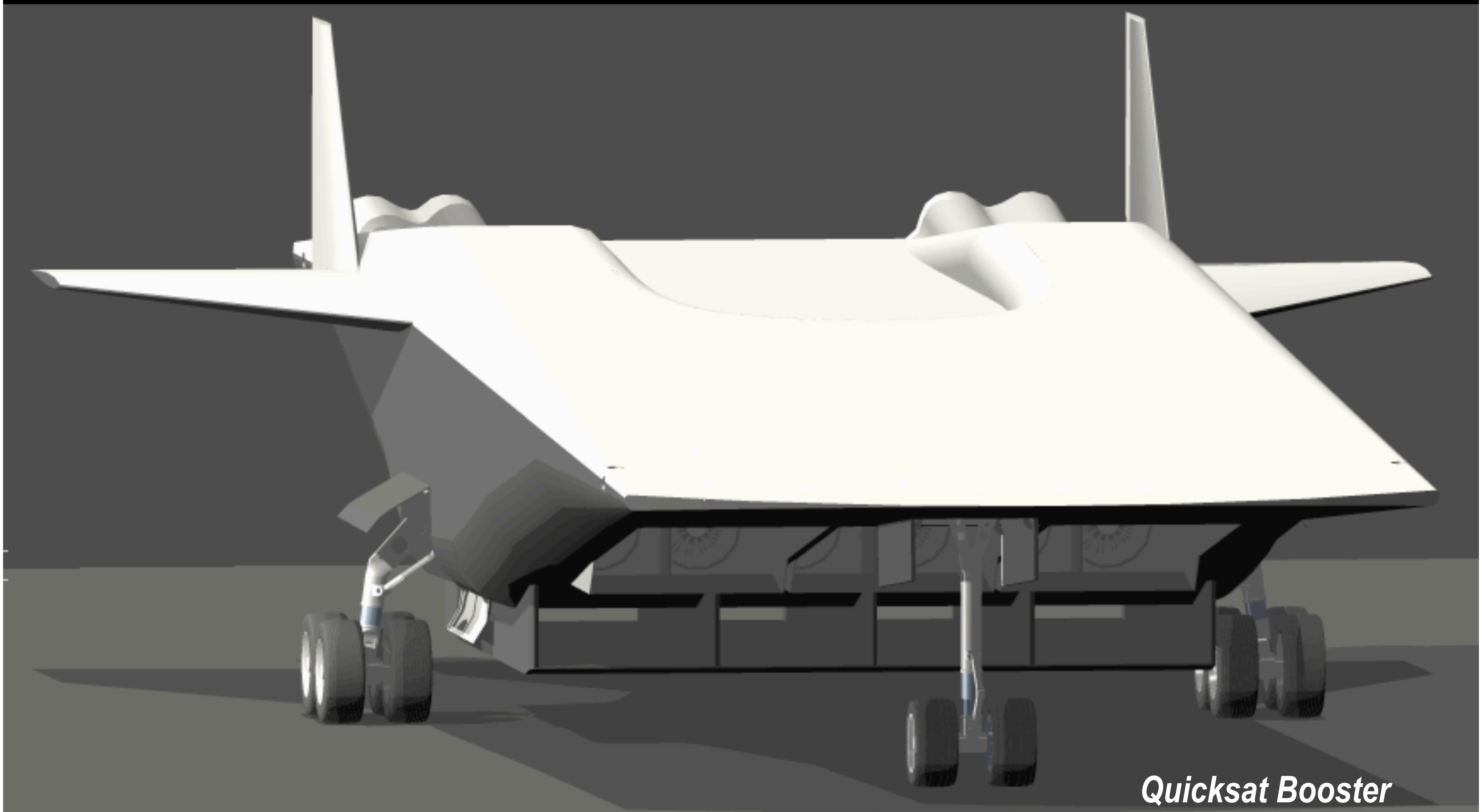
Summary and Conclusions

Summary:

- Over the course of the last two years and with funding from the AFRL, SEI has been performing the conceptual design of two MSP concepts called *Quicksat* and *Sentinel*
  - *Quicksat* is a TSTO MSP that uses TBCC and DMSJ propulsion systems and H_2O_2/JP-7 propellants
  - *Sentinel* is a TSTO MSP that uses RBCC propulsion and LOX/JP-7 propellants
- These vehicles were designed in a multidisciplinary environment using Phoenix Integration's ModelCenter® and Analysis Server software products to establish an automated vehicle closure model
- The engineering toolset consisted of industry-standard and in-house codes spanning propulsion, trajectory, aerodynamics, aeroheating/TPS, and weights & sizing
- Once established, the vehicle closure models were used to quickly perform a number of trade studies and sensitivity analysis
- The construction of the ROSETTA meta-model was facilitated by the use of Pi Blue's ProbWorks suite and subsequently used to perform a probabilistic sensitivity analysis on the *Sentinel* vehicle concept

Conclusions:

- The closure model's initial setup time was more than offset by later time and work savings
- Disciplinary tools distributed across multiple machines and computing platforms executed and exchanged data seamlessly
- The use of ModelCenter® came with additional benefits inherent in the software such as a single location data repository, process repeatability, and access to additional system analysis tools (ProbWorks, OptWorks, etc.)
- ModelCenter® enabled faster exploration of the design space, compared to what could be accomplished without its use for equivalent resources, and thus facilitated a greater understanding of the vehicle concepts


Quicksat Booster


OF
Sentinel Booster

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